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On the simulation of panel distortions due to hot curing adhesives

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ABSTRACT

Hot curing one-part adhesives are often used to bond car body shells. The cure process of the adhesive, however, can lead to distortions, *i.e.* unwanted, visible deformations of the adherends. In case of outer car panels, these distortions are considered as visual defects, even though the structural integrity might not be affected. In order to avoid distortions by a proper control of the bonding process, a thorough understanding of the development of distortions is necessary. Finite element simulations can help to gain insight into this development. In this work, a simulation model is proposed and used to study the appearance of distortions in a steel sheet over different temperature cycles. The model takes chemical shrinkage and thermal deformation as well as gelation and stress relaxation into account. It was found that the heating rate can affect distortions. Lowering the cure temperature only lowers distortions for high temperature rates. Low heating rates can reduce distortions.

1. Introduction

Adhesive bonding is a widely-used joining technology in automotive industry. Hot-curing one-part adhesives are well suited for car body manufacturing because of their good oil absorption and flexible applicability. Bonding processes with this type of adhesive are not restricted by pot life or assurance of a correct mixture ratio. Moreover, the necessary heat treatments can be combined with heat treatments in the baking process after electrophoretic coating. By that, production steps can be reduced. The cure process of the adhesive at elevated temperatures, however, can lead to distortions, *i.e.* unwanted, visible deformations of the structure, especially when thin-walled structures as outer car panels are involved. These distortions can occur along the bond line (local distortions) or affect the entire geometry (global distortions). Adapting the production process or repair work can be costly and time-consuming, once these defects occur. Therefore, it is desirable to predict distortions before they arise and modify manufacturing accordingly to prevent them. Several constitutive models of curing polymers have been successfully used to predict residual stresses in composite manufacturing and other processes (Kiasat, 2000; De Vreugd et al., 2010; Jansen et al., 2012). With regard to car panel distortion, however, models mainly focused on the cooling down phase (Hahn and Jendrny, 2003; Fuchs et al., 2010). These models do not allow for following the development of distortions over the entire cure cycle. They assume a stress-free state when the cooling down sets in. But investigations on residual stresses in laminates show that the structure is not warpage-free if heated up, again, to cure temperature after manufacturing (Gigliotti et al., 2003). The objective of this work is to build up a simulation model for local panel distortions, which is capable of predicting the development of distortions over different cure cycles. It should take known phenomena of curing polymers into account. By that, it will be a basis for analyzing bonding processes with regard to panel distortions.

2. Background

A main cause for panel distortions is the combination of changing properties of the adhesive. During the bonding process the adhesive develops from a viscoelastic liquid to a viscoelastic solid (Ferry, 1980; te Nijenhuis, 1997). At the same time the adhesive's specific volume changes. Due to the cross-linking of polymer chains the density of the adhesive increases. This process is referred to as chemical or reactive shrinkage. The changing temperature leads to additional thermal deformation of the adhesive. The evolving properties of the adhesive are considered the main cause for local distortions, *i.e.* deformations close to the bond line. Therefore, they are the main focus of this work. But it should be emphasized that further phenomena play a role in panel distortions. The temperature cycle can cause relative movements of the adherends

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during the bonding process (Eis, 2000; Hahn and Jendrny, 2003). These displacements depend on boundary conditions of the bonding process such as geometry and fixture of the structure, temperature field in the oven (Blanke, 2009) and the thermal expansion and conductivity of the adherend materials. Especially in multi-material design, different coefficients of thermal expansion (CTE) can lead to thermally induced relative movements during the bonding process which remain after the cure cycle. This "α-mismatch" problem has been subject to numerous research activities (Hahn and Hüsgen, 1991; Hahn et al., 1993; Meschut et al., 2003a,b; Meschut and Gänsicke, 2003).

While several experimental investigations focus on a final state of distortions after the cure process (Andersson, 2009; Bouten, 1990; Fernholz et al., 2007; Patankar et al., 2013), in some works their development over the temperature cycle is examined (Priesnitz et al., 2014; Chudaska and Hahn, 1993, 1994a,b; Hahn et al., 1999). These publications show that significant deformation develops in the cooling phase. But even in the heating and holding phase of a temperature cycle deformation can arise. Changes to the temperature cycle (such as cure temperature, dwelling periods, heating and cooling rates) affect significantly residual stresses and the properties of the adhesive bond (Mathias, 1989; White and Hahn, 1993; Hahn et al., 1993). This knowledge is already applied in cure cycle optimization. White and Hahn (1993) found that dwelling at elevated temperatures before the final cure temperature is reached can reduce residual stresses in composites.

Besides experimental research there have also been several different approaches to predict residual stresses in composites (Dano and Hyer, 1998, 2002; Lopes et al., 2007) or adhesive bonds (Hahn and Jendrny, 2003; Fuchs et al., 2010; Patankar et al., 2013). Prediction models based on elastic material behavior (Hahn and Pagano, 1975; Plepys et al., 1994; Yu et al., 2006; Basu and Kia, 2008; Jumbo et al., 2010) are available as well as models based on viscoelasticity (Hahn and Jendrny, 2003; Fuchs et al., 2010; Patankar et al., 2013). These approaches take only the cooling down phase into account. Stresses in the heating and holding phase are neglected. Other constitutive models of curing polymers (Adolf and Martin, 1996; Adolf and Chambers, 2007; De Vreugd et al., 2010; Liebl et al., 2012a,b; Jansen et al., 2012; Kiasat, 2000) allow to capture the full cure cycle. They indicate that stresses can occur before the cooling down sets in. These models have been successfully applied to coating processes (Jansen et al., 2012), electronic packaging (De Vreugd et al., 2010) and composites manufacturing (Kiasat, 2000). An application to local panel distortions due to adhesive bonding is missing.

In some prediction models the chemical shrinkage is not accounted for (Hahn and Jendrny, 2003; Basu and Kia, 2008). Some authors argue that the contribution of chemical shrinkage to residual stresses is small (Hahn and Orth, 1997; White and Hahn, 1992). Genidy et al. (2000) state that the low influence of chemical shrinkage on residual stresses in composites predicted in reference White and Hahn (1992) is due to an underestimation as further experimental work by the same authors show (White and Hahn, 1993). Other investigations on the development of panel distortions (Priesnitz et al., 2014; Chudaska and Hahn, 1994a) indicate a significant deformation before the cooling down sets in. Chudaska and Hahn (1994a) reason that this displacement is caused by chemical shrinkage of the adhesive. de Vreugd (2011, p. 70) points out, that standard tests for measuring chemical shrinkage are performed by measuring volumes at ambient temperature before and after curing. But the shrinking process takes place at elevated temperatures. Therefore, he measures changes in the specific volume over a full temperature cycle. A three-dimensional simulation model on distortion development would give insight in how chemical shrinkage and other changing material properties mentioned above contribute to the development of local panel distortions.

3. The model

In this work, a simulation model for developing local distortions due to hot curing adhesives is proposed. The cure process is assumed to be quasi-static. In that case, the balance of linear momentum can be expressed by the equation

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0, \tag{1}$$

where σ_{ij} is the Cauchy stress tensor. In addition, it is assumed that the state of cure can be described by a single variable q, the degree of cure. The cure evolution is described by the Kamal–Sourour equation for auto-catalytic reactions (Sourour and Kamal, 1976)

$$\dot{q} = k_0 \exp\left[-\frac{E_a}{RT}\right] q^m (1-q)^n, \tag{2}$$

where $R = 8.314$ J/(mol K) is the ideal gas constant; the material parameters k_0, E_a, m and n need to be determined by fitting the equation to experimental data. To avoid $q = 0$ for all times, $q_0 = 0.01$ is chosen as an initial value for q instead of zero for all calculations.

An important part of a simulation model are the material equations for the adhesive. The adhesive is assumed to be isotropic. As in other works (Yagimli and Lion, 2011; Liebl et al., 2012a), this model is based on an additive decomposition of the strain tensor. Here, ε_{ij} is split in a mechanical, a thermal and a chemical part:

$$\varepsilon_{ij} = \varepsilon_{ij}^{\mathrm{me}} + \varepsilon_{ij}^{\mathrm{th}} + \varepsilon_{ij}^{\mathrm{ch}}. \tag{3}$$

Since the mechanical properties of the adhesive change significantly over a cure cycle, the process is divided into three stages. In each of these stages the mechanical behavior is described by different constitutive equations. The gel point and the glass transition represent the transition points between the stages (see Fig. 1).

3.1. Stage I

te Nijenhuis (1997) describes the gel point as the moment where the material develops an equilibrium shear modulus. With the equilibrium shear modulus being zero, *i.e.* before the gel point is reached, the adhesive is a viscoelastic liquid (Ferry, 1980). In that state, the polymer cannot build up static stresses other than hydrostatic ones. Therefore, thermal and chemical strain cannot contribute to residual stresses. They are not calculated in stage I.

3.2. Stage II

In stage II, residual stresses can start to build up. The constitutive equations used here to describe the behavior of the adhesive are based on De Vreugd et al. (2010), de Vreugd (2011), Jansen et al. (2012) and Adolf and Martin (1996). Typical cure cycles for automotive adhesives have high cure temperatures to minimize the curing time. These cure temperatures are usually high above

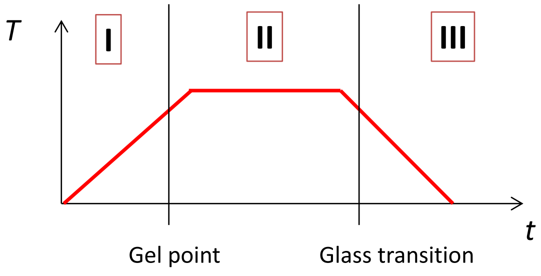

Fig. 1. Three different stages of the temperature cycle.